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Investigating the Economic Value of Flexible Solar Power Plant Operation

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Energy+Environmental Economics

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Abstract

Solar power is growing rapidly around the world, driven by dramatic cost reductions and increased interest in carbon-free energy sources. Solar is a variable resource, requiring grid operators to increase the available operating range on conventional generators, sometimes by committing additional units to ensure enough grid flexibility to balance the system. At very high levels of penetration, operators may not have enough flexibility on conventional generators to ensure reliable operations.

However, modern solar power plants can be operated flexibly; in fact, they can respond to dispatch instructions much more quickly than conventional generators. Flexible solar not only contributes to solving operating challenges related to solar variability but can also provide essential grid services. This study simulates operations of an actual utility system – Tampa Electric Company (TECO) – and its generation portfolio to investigate the economic value of using solar as a flexible resource. The study explores four solar operating modes: "Must-Take," "Curtailable," "Downward Dispatch," and "Full Flexibility."

The study finds that for this relatively small utility system, *Must-Take* solar becomes infeasible once solar penetration exceeds 14% of annual energy supply due to unavoidable oversupply during low demand periods, necessitating a shift to the *Curtailable* mode of solar operations. As the penetration continues to grow, the operating reserves needed to accommodate solar uncertainty become a significant cost driver, leading to more conservative thermal plant operations and increasingly large amounts of solar curtailment. Flexible solar reduces uncertainty, enabling leaner operations and providing significant economic value. At penetration levels exceeding 20% on the TECO system, solar curtailment can be reduced by more than half by moving from the *Curtailable* to the *Full Flexibility* solar operating mode. This results in significant additional value due to reduced fuel costs, operations and maintenance costs, and air emissions.

Finally, the study evaluates the impact of flexible solar in combination with energy storage. We find that flexible solar can provide some of the same grid services as energy storage, thereby reducing the value of storage on a high-solar grid.

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1 Introduction

Solar electricity is becoming an important part of the electric generation portfolio in many regions due to rapidly declining costs and policies favoring non-emitting renewable generation. The installed capacity of solar has grown exponentially over the past two decades.

Further solar growth is expected in subsequent decades. Policy targets for renewable energy installation and decarbonization of the energy system are driving solar installations around the world. Both India and China have targets to reach more than 100 GW of installed solar capacity by the early 2020s.[1] California and Hawaii have passed legislation to reach 100% renewable or zero-carbon electricity by 2045, and it is expected that solar energy will be one of the primary energy sources used meet these ambitious targets. Recent analysis on deep decarbonization pathways in California suggests that solar power could supply a large fraction of the economy-wide demand for energy by 2050.[2] Europe is also expected to increase solar energy capacity to meet decarbonization targets.

1.1 Operational challenges and opportunities

Existing or "conventional" utility-scale solar is typically designed and operated to generate and deliver the maximum amount of electricity in real-time. This approach is motivated by the desire to minimize the cost per unit of energy by amortizing the capital cost of solar across the maximum amount of energy that system could produce.

Increasing the level of solar can make it more challenging for grid operators to balance electricity supply and demand. For example, grid operators must manage rapid increases in solar generation during sunrise

[1] International Energy Agency, "IEA/IRENA Joint Policies and Measures Database: Global Renewable Energy," accessed September 2018, https://www.iea.org/policiesandmeasures/renewableenergy/.
[2] A. Mahone, Z. Subin, J. Kahn-Lang, D. Allen, V. Li, G. De Moor, N. Ryan and S. Price, "Deep Decarbonization in a High Renewables Future: Updated Results from the California PATHWAYS Model," Energy and Environmental Economics, Inc., June 2018, https://www.ethree.com/wp-content/uploads/2018/06/Deep_Decarbonization_in_a_High_Renewables_Future_CEC-500-2018-012-1.pdf.

and rapid decreases in solar production during sunset, in addition to variations in solar output caused by regional weather conditions. This often requires managing ramping events by rapidly varying the output of conventional thermal generation. At higher levels of solar penetration, operational challenges become more acute.

Many operational challenges can be addressed by making utility-scale solar available to provide flexibility for grid operations when needed. For example, ramping demands on conventional generation resources can be reduced if solar plants can control ramp rates during both morning and evening hours, thereby providing the means to flexibly operate the grid even in the presence of higher levels of solar generation. While operating solar generators in a flexible manner leads to occasional curtailment of solar output, this may still be a more economical operating mode than other options.

Recent studies have shown that utility-scale solar photovoltaic (PV) plants can provide essential grid reliability services that are typically associated with conventional generation.[3] In the most recent study, First Solar teamed with the National Renewable Energy Laboratory (NREL) and the California Independent System Operator (CAISO) to test a 300 MW utility-scale photovoltaic power plant in California. The power plant was equipped with advanced power controls by combining multiple power-electronic inverters and advanced plant-level controls. The test demonstrated that PV plants can have the technical capabilities to provide grid services such as spinning reserves, load following, voltage support, ramping, frequency response, variability smoothing, frequency regulation, and power quality improvement. Specifically, the tests included various forms of active power controls such as automatic generation control and frequency regulation, droop response, and reactive power/voltage/power factor controls. The results showed that regulation accuracy by the PV plant is significantly better than fast-ramping gas turbine technologies.

By leveraging the full suite of operational capabilities of utility-scale solar resources, solar can go beyond a simple energy source and become an important tool to help operators meet flexibility and reliability

[3] See V. Gevorgian and B. O'Neill, "Advanced Grid-Friendly Controls Demonstration Project for Utility-Scale PV Power Plants," National Renewable Energy Laboratory, January 2016, https://www.nrel.gov/docs/fy16osti/65368.pdf; M. Morjaria, D. Anichkov, V. Chadliev and S. Soni, "A Grid-Friendly Plant: The Role of Utility-Scale Photovoltaic Plants in Grid Stability and Reliability," IEEE Power and Energy Magazine, vol. 12, no. 3, 2014; and California ISO, National Renewable Energy Laboratory, and First Solar, "Using Renewables to Operate a Low-Carbon Grid: Demonstration of Advanced Reliability Services from a Utility-scale Solar PV Plant," 2017, https://www.caiso.com/documents/usingrenewablestooperatelow-carbongrid.pdf

needs of the grid. To date, the economic value of including solar as an active participant in balancing requirements has not been widely studied. To quantify the value of flexible solar operation, our study introduces solar flexibility constraints into a detailed multi-stage production cost model. We do not explore the economic value of voltage control in this study.

Recent cost declines in energy storage technologies enable solar to further extend its capability by providing firm dispatchable capabilities, which in turn enables even higher solar penetrations. Adding storage to the grid can shift energy to when it is most needed, even if the sun has already set. Adding storage to a grid can combine the flexibility of solar with the firm capacity and energy shifting capabilities of storage, but requires significant capital investment in storage resources. The last section of this study investigates the interplay of solar flexibility and storage value.

1.2 Uncertainty and variability in grid operations

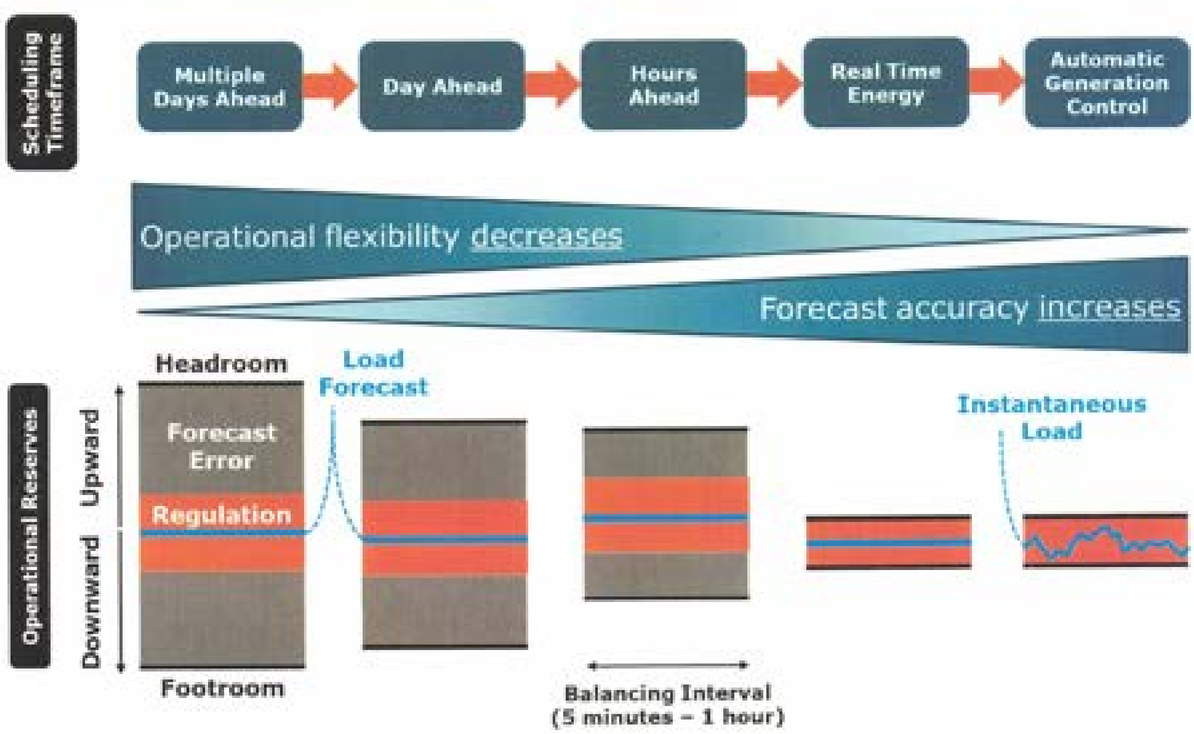
Much like musicians following the conductor in an orchestra, the system operator coordinates the dispatch of an ensemble of power plants. The system operator's goal is to meet demand at least cost while maintaining reliability.

Operational challenges are often described using the terms *variability* and *uncertainty*. Variability refers to increases and decreases in demand or resource availability that would exist even with a perfect forecast. For example, diurnal patterns in human activity are a source of demand variability because these patterns occur naturally over the course of a day. Uncertainty represents the inability to perfectly forecast future demand or other grid conditions. Even in the absence of wind and solar power plants, system operators must maintain system reliability at all times under significant variability and uncertainty of demand, as well as uncertainty with respect to generator and transmission availability.

To balance the system, operators must have information about the level of uncertainty in their forecasts as well as the capabilities of their resources to respond. Forecast accuracy increases closer to real time, but the ability to respond to unexpected events decreases because the operating range of conventional power plants is smaller over shorter time intervals. This problem is magnified by the challenges of generator scheduling ("unit commitment"), because thermal generators typically require significant lead time – hours to days, or even weeks – to be turned on or off. Once running, thermal plants must generate at minimum levels that are typically at least 20 – 50% of maximum output. For some coal-fired generation, the minimum generation level can be as high as 70%. Thus, system operators must frequently make decisions about which units will be operating and at what levels far in advance, and with imperfect information about the level of demand and renewable production.

If actual demand turns out to be much higher than forecasted, there may not be enough resources available to meet demand. To deal with this uncertainty, grid operators maintain a safety margin on top of forecasted demand ("headroom") when scheduling power plants so that a demand under-forecast does not turn into a power shortage. This is shown schematically in Figure 1. In the opposite direction, operators may also retain the ability to turn down or turn off generation ("footroom") to avoid oversupply conditions in the event of a demand over-forecast.

Figure 1: Commitment timeframes, forecast uncertainty, headroom and footroom



System operators are constantly balancing economics and reliability when making commitment and dispatch decisions. If they are conservative and commit too many power plants, generators will be forced to run at less efficient set points or cycle on and off quickly, both of which can be costly. If operators are not conservative enough, they may have to buy expensive energy from neighbors in real-time, call on expensive demand response resources, or incur penalties for violating reliability standards. The worst case is that there simply is not enough generation capacity committed to serve demand and the operator must temporarily disconnect customer loads.

In addition to the challenges of forecasting demand long before real-time, operators must also be prepared for the natural variability of demand in real-time. Common practice is to hold headroom and footroom on quick-moving units ("regulation") to ensure adequate flexibility. Organized markets – the California Independent System Operator (CAISO), the Electric Reliability Council of Texas (ERCOT), PJM Interconnection, the Midcontinent Independent System Operator (MISO), etc. – procure regulation as part of market operations, and centrally dispatched utilities typically have a similar requirement in their dispatch procedures. Operators also address variability by committing units more frequently closer to real-time operations. It is common to commit and dispatch generators on an hourly basis a day-ahead of real-time, and every five to fifteen minutes during real-time operations.

Increasing the level of solar (and wind) generation on the grid increases the variability and uncertainty of electricity supply, both because of imperfect forecasts of wind and solar output and because of fluctuations in output on a minute-to-minute basis. This frequently increases the overall forecast error and regulation requirements needed to balance supply and demand. Higher balancing requirements raise the stakes of power plant commitment decisions.

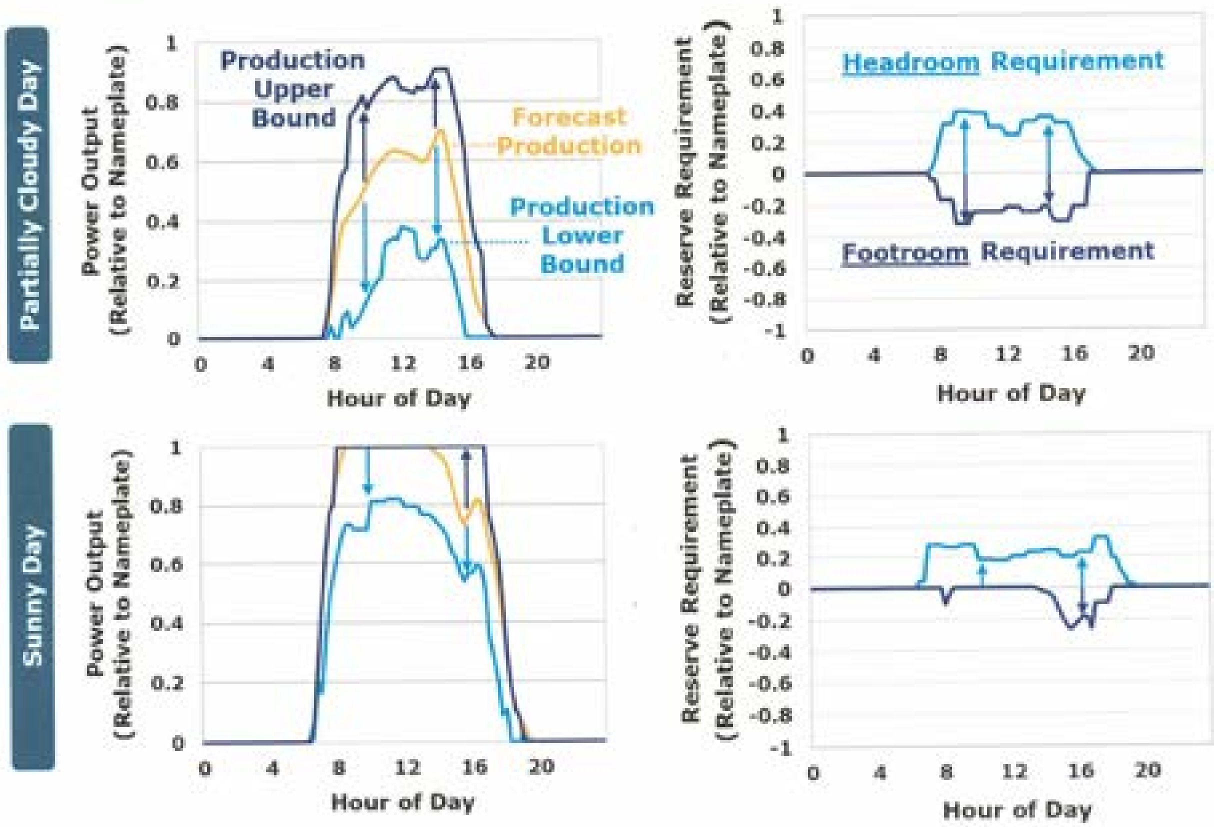
1.3 System balancing with flexible solar generators

Many modern solar power plants have the technical capabilities to contribute to regulation and balancing requirements through precise output control – this is referred to as "flexible" or "dispatchable" solar. In this operating mode, the entire suite of solar dispatch capabilities is made available to the system operator in determining economic dispatch. System operators can elect to use the solar resources to provide energy or essential grid services (e.g., regulation reserves), and this choice may vary by dispatch time interval throughout the day. Provision of these services requires downward dispatch of solar, and some services require the plant operator to maintain headroom to enable upward dispatch. While this results in lost solar production, solar plants incur no measurable variable costs from providing these services. Instead, the cost of solar providing these services is an opportunity cost that can be estimated in the context of economic dispatch. Obtaining grid services from solar plants can, in some instances, enable system operators to reduce fuel costs by reducing thermal generator commitments and increasing the efficiency at which they operate.

Sourcing essential grid services from solar requires the system operator to have an appropriate degree of confidence in the level of solar output minutes, hours, or days ahead of real-time dispatch. As shown in Figure 2, historical solar forecast errors can be used to calculate expected lower and upper bounds on solar production when making commitment decisions ahead of real-time. The lower and upper bounds are used to 1) set system-wide headroom and footroom needs for solar forecast error, and 2) if solar is represented as dispatchable, set limits on how much the solar plant could be dispatched. There are a variety of means for establishing confidence bounds, and this would be an interesting topic for future research. For the current study, we use a single standard deviation above and below the solar forecast as the upper and lower bounds when committing units ahead of real-time.

Our study focuses on the flexible operation of solar power plants in the absence of battery storage. To date, much emphasis has been placed on the role that storage can play in managing solar and wind variability and uncertainty. In this study, we focus on the operation of the solar or wind power plants themselves, and the economic benefits that may result from operating these assets in a more flexible manner. Interactions with battery storage value are explored in a sensitivity study.

Figure 2: Confidence in solar forecasts hours ahead of real-time (left) and resulting forecast error reserve levels (right) on an example partly cloudy day (top) and sunny day (bottom), normalized to solar power plant capacity. As discussed below, reserve requirements must be met by non-solar resources if solar flexibility is not integrated into system operator dispatch procedures, but can be partially met by solar power plants when solar is represented as more flexible.



1.4 Solar operating modes

In this study we explore different solar "operating modes," which represent the extent to which system operators have incorporated the inherent flexibility of many modern utility-scale solar power plants into their operational procedures. We define four solar operating modes to explore the value of solar dispatch flexibility, ordered from least to most flexible:

Solar Operating Mode	Solar can be curtailed	Solar can contribute to footroom requirements	Solar can contribute to headroom requirements
Must-Take	×	×	×
Curtailable	✓	×	×
Downward Dispatch	✓	✓	×
Full Flexibility	✓	✓	✓

In the Must-Take and Curtailable operating modes, other resources – in this study, thermal generators and batteries – are committed such that solar can produce at maximum possible output even in the case of solar under- or over-forecast. In the Downward Dispatch operating mode, solar can be dispatched downward (curtailed) to meet footroom requirements but cannot contribute to headroom requirements. In the Full Flexibility operating mode, solar can be fully dispatched to meet grid needs via economic optimization of energy production and operational reserves while accounting for physical limits imposed by solar insolation availability. When solar is scheduled to be curtailed ahead of real-time, the amount of forecast error headroom that is held on other resources is reduced.

Renewable integration studies include a range of assumptions with respect to solar (or wind) operating modes. Most studies simulate solar (or wind) in Curtailable or Downward Dispatch operating mode, though the implementation of solar operating mode in these studies depends on modeling methodology and may not map precisely onto the operating modes defined above. A smaller set of studies explores the Full Flexibility operating mode for solar, frequently as a sensitivity study. Appendix B, "Prior Research," contains citations to example renewable integration studies.

1.4.1 MUST-TAKE OPERATING MODE

Many system operators and solar integration studies treat solar power plants as "must-take." The common convention is to subtract solar production from electricity demand, which assumes there is neither the ability nor the desire to control solar output. The resulting "net load" is the amount of power that must be produced by other "dispatchable" resources.

Quick thought experiments demonstrate that the concept of net load was not designed for high penetrations of solar. What if there is so much solar on the grid that there is more solar electricity production than demand? In this scenario, net load would be negative. Balancing supply and demand with negative net load would be very challenging, requiring some level of exports, flexible demand, or energy storage. In the extreme case, the system simply cannot be brought into balance without drastic action such as the temporary disconnection of generators. The term "solar overgeneration" has been used to describe the situation of solar production levels that exceed the ability of the power system to absorb all solar generation. Challenges related to overgeneration and system balancing led early analyses to conclude that power systems could accept only a small fraction of annual energy penetration from variable renewables (wind and solar) before encountering reliability challenges.

It is worthwhile to note that present-day rooftop solar installations are operated as "must-take" because they are almost never visible to or curtailable by the system operator. One of the corollaries to this study's conclusions is that reaching high rooftop solar penetrations will require some control of these resources – operator dispatch signals, pricing mechanisms, local autonomous control, or other control methods.

The CAISO's widely-circulated "duck curve" is a prominent example of operational concerns in the context of must-take solar.[4] Figure 3, based on the duck curve, demonstrates this phenomenon for a system with limited ramping capability. In the left panel, operational limitations lead to a reliability problem: unserved energy, which occurs when the system cannot ramp up fast enough to meet high demand in the evening. In the right panel, prospective curtailment of renewable generation has been used to avoid loss of load by ensuring that sufficient upward ramping capability is online and available. However, this strategy comes at the cost of lost renewable production.

[4] California ISO, "What the duck curve tells us about managing a green grid," 2016, https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

Figure 3: Prospective curtailment of renewable energy resources eliminates a reliability challenge, but introduces an economic challenge

1.4.2 CURTAILABLE OPERATING MODE

As solar penetration has increased, curtailment of solar output has become a reality during hours in which inflexibility, lack of load, or transmission constraints prevent absorption of all available solar energy. Curtailment can occur through analog means if necessary – for example, a phone call from the system operator to the plant operator requesting a reduction in output. Increasingly, solar and wind generators are providing decremental energy bids into organized markets such as CAISO, MISO and ERCOT, enabling curtailment to occur as a market outcome rather than through an emergency phone call. In many instances, power purchase agreements (PPA) between independent power producers (IPP) and utility off-takers of solar project output have evolved to accommodate some degree of curtailment flexibility to reflect this emerging reality. Many regions (e.g., Germany, Denmark, California, Hawaii, etc.) have successfully reached higher penetrations of variable renewables – as high as 42% of annual energy in the case of Denmark – by using renewable curtailment and interties with neighboring regions as important integration tools.[5]

Solar curtailment to date has been largely, if not exclusively, focused on avoiding oversupply. Even though solar output can be controlled to an extent, many renewable integration studies and grid operators continue to include solar forecast error in their calculations of headroom and footroom balancing

[5] A. Bloom, U. Helman, H. Holttinen, K. Summers, J. Bakke, G. Brinkman and A. Lopez, "It's Indisputable: Five Facts About Planning and Operating Modern Power Systems," IEEE Power and Energy Magazine, 2017.

requirements while excluding solar generators from meeting any portion of those requirements. In other words, solar can be curtailed during normal grid operations, but regulation and forecast error reserve requirements are still determined based on net load and must be met by resources other than solar generators. We refer to solar operated in this mode as "Curtailable," since curtailment is used only to avoid oversupply and the precise control of solar output is not considered in generator scheduling and economic dispatch.

1.4.3 DOWNWARD DISPATCH OPERATING MODE

The deployment of more variable renewable capacity has increased the need for "downward" flexibility, or footroom. If renewable production unexpectedly increases, other resources must ramp downward to accommodate the additional energy flowing onto the system. This is particularly a concern in real-time, after commitment decisions have been made. In this case, insufficient footroom might result in large quantities of energy flowing onto neighboring systems, violating North American Electric Reliability Corporation (NERC) control performance standards.

However, if the system operator can control output from the solar plant in real-time, it is possible to reduce solar generation to avoid overgeneration conditions. Utilizing the footroom that is available on a flexible solar resource reduces or eliminates the need to hold footroom on other resources to accommodate unexpected spikes in solar production. Stated differently, solar can provide its own downward reserves or footroom. Consequently, our simulations with the Downward Dispatch solar operating mode system operations do not require any footroom for solar uncertainty and variability.

But solar that can be dispatched downward is not limited to providing *its own* footroom – it can also provide footroom to accommodate unexpected decreases in *demand*. In other words, flexible solar can be used to provide the downward regulation service that system operators have for more than a century sourced exclusively from conventional generators. If enough solar is forecasted to be online in real-time, operators can plan to dispatch solar downwards if demand drops unexpectedly. In this study, we limit the footroom that solar can provide for meeting variability and uncertainty in demand to the lower bound of forecasted solar production potential – the distance between zero and the light blue Production Lower

Bound line in Figure 2. This limit ensures that footroom on solar will be available even if solar generation is over-forecasted.

One potential issue with relying on variable renewables for balancing services is that the operator cannot be certain that the resource will produce enough power to provide the balancing service. This concern is minimal in the case of solar footroom, because the service is needed predominantly *during the times when solar is producing too much energy*. Our production simulation results do not show any significant overgeneration events in real-time even at very high solar penetration levels, indicating that system operators can rely on solar to provide footroom when necessary. With enough flexible solar on the grid, it is unlikely that system operators will have reliability concerns related to downward flexibility in the daytime, although operators will continue to need footroom to cover load variations during nighttime hours.

1.4.4 FULL FLEXIBILITY OPERATING MODE

In this study, the Full Flexibility solar operating mode includes the most options of any operating mode for solar to contribute to essential grid services, and the highest degree of integration of solar resource characteristics into system operator dispatch procedures. The Full Flexibility operating mode includes all the footroom capability of solar from the Downward Dispatch operating mode but also allows solar to provide headroom (upward) flexibility.

Relying on solar to provide *headroom* (regulation up, spinning reserve, etc.) requires 1) plant output to be curtailed intentionally or under-scheduled (scheduled below the maximum available energy production) in order to create headroom, and 2) system operator confidence that additional solar production potential will be realized if called upon. We posit that solar can be forecasted with sufficient confidence within a lower bound as discussed above, but we recognize that system operators will naturally be conservative when relying on solar in the upward direction.

Under-scheduling solar reduces the uncertainty of solar production, and therefore the headroom that would be required for solar forecast error. For example, if at the day-ahead scheduling period it is anticipated that solar would be curtailed on the operating day due to oversupply, system operators can reduce the amount of headroom they would otherwise procure to accommodate a potential solar over-forecast. Put another way, headroom needed on other resources for solar forecast error is reduced when the operator forecasts the need to curtail solar before real-time.

In addition to reducing headroom reserves associated with solar forecast error, under-scheduled solar could be a potent provider of upward ramping service. Solar power plants can ramp up much more quickly than their conventional counterparts, suggesting that solar may be particularly well suited to provide frequency regulation or fast frequency response. This is especially true given that the supply of these fast-timescale balancing services tends to be the most limited during times of low demand and high variable renewable production.

In this study, we have allowed solar to provide upward regulation with available headroom. To ensure that the regulation headroom on solar is available in real-time, we require that additional forecast error headroom is held on other resources when scheduling solar regulation capacity before real-time. A summary of how solar provides headroom and footroom in this study is presented in Table 6 in Appendix A. We do not simulate the provision of fast frequency response in this study, nor do we simulate solar providing contingency reserve and headroom for load under-forecast events, although we believe it should be possible for solar to provide these services given enough certainty on solar production potential. This means that there may be additional value for solar headroom that is not included in this study, especially at higher solar penetration levels.

2 Description of Case Study

2.1.1 SYSTEM DESCRIPTION

To demonstrate the economic value of dispatching solar, we use the PLEXOS Integrated Energy Model to simulate unit commitment and dispatch of an actual utility system – Tampa Electric Company (TECO). TECO has good solar resource availability and a peak demand of ~ 5 GW. TECO operates its electricity system as a Balancing Authority.

TECO was an active participant in the study and provided data on its system, including real-time and forecast demand data, fuel cost projections, and detailed, unit-specific information on its thermal generation portfolio. Our study represents a snapshot of the TECO system in 2019.

TECO's thermal generation portfolio is similar to that found in many areas of the United States and other countries, making the results of this study broadly applicable. The expected 2019 portfolio consists of 60% of thermal capacity from natural gas combined cycle units, 6% from natural gas simple cycle combustion turbines, 20% from natural gas steam turbines, and 13% from coal steam and integrated gasification combined cycle units. TECO's generation portfolio does not include nuclear, wind, other renewable resources, or substantial behind-the-meter solar.

2.1.2 SOLAR DEPLOYMENT LEVELS

We simulate a range of utility-scale solar deployment levels ranging from 0% (no solar) to 28% annual energy penetration potential. The upper end of this range represents higher levels of solar energy than are currently operational in any balancing area in the United States. Annual solar energy penetration potential refers to the amount of energy available from a given capacity of solar energy facilities – the amount that would be produced in the absence of curtailment – normalized to annual balancing area electricity demand. We simulate each penetration level with four different solar operating modes: Must-Take, Curtailable, Downward Dispatch, and Full Flexibility.

This study focuses on operational cost savings of adding solar generation assets to the electricity system and does not include a full cost-benefit analysis of solar deployment. The solar penetration levels studied herein are academic in nature and are not indicative of TECO's future resource acquisition plans. TECO is currently developing 600 MW solar (~7% annual energy penetration) and a 10 MW / 27 MWh storage facility.

2.1.3 SOLAR PRODUCTION DATA

It is important to retain correlations between solar availability and weather-driven heating and cooling loads. We accomplish this by using historical data from 2017 as the basis of load and solar profiles. For demand, 2017 demand profiles are scaled to 2019 using projected 2019 annual TECO demand. For solar, TECO identified 15 sites in its service territory that are being considered for solar development. Locus Energy produced simulated 5-minute solar insolation data from 2017 for each site, and First Solar transformed the insolation data into solar plant output potential. We aggregate solar profiles for the 15 sites into a single TECO-wide solar profile and scale this profile to installed solar capacity. This approach assumes that all solar development occurs within TECO's service territory – a relatively small portion of the Florida peninsula – which therefore would not materially increase the geographic diversity of TECO's solar resources at higher levels of solar penetration. It may be possible to reduce the variability and uncertainty of solar generation by deploying solar power plants over a larger footprint.

Historical solar forecast data is not available from the Locus Energy dataset, so we synthesize solar forecasts through a day-matching algorithm utilizing a National Renewable Laboratory (NREL) solar dataset.[6] Three separate forecast error profiles from the Tampa area were averaged to generate one TECO-wide profile. The NREL dataset contains forecasts for one day ahead and four hours ahead of real-time, but TECO also uses forecasts to make commitment decisions for coal and gas steam units many days ahead of real-time. To generate multiple day-ahead solar forecasts, we simply use the month-hour

[6] National Renewable Energy Laboratory, "Solar Power Data for Integration Studies," accessed March 2018, https://www.nrel.gov/grid/solar-power-data.html.

average of the First Solar output profiles. Figure 4 shows how solar forecasts change ahead of real-time operations.

Figure 4: Solar profiles used for unit commitment across different timeframes from an example June day. Profiles are for 600 MW of installed solar capacity.

2.1.4 PLEXOS PRODUCTION COST MODEL

System operators have imperfect information about future grid conditions when making key operational decisions. The PLEXOS model we use in this study optimizes system unit commitment and dispatch for each day of the year in four sequential stages: multiple days-ahead, day-ahead, hours-ahead, and real-time (Table 1). The goal of each stage of the model is to represent the quality of information that TECO system operators would have at key operational decision points. To this end, load and solar production profiles are updated with better forecasts after each stage.

Table 1. PLEXOS model stages

Unit commitment stage	Dispatch and commitment decision timestep	Look-ahead length (after operating day)	Load timeseries data (provided by TECO)	Solar timeseries data
Multiple days-ahead	Hourly	Six days	Multiple days ahead forecast	Month-hour average of 5-minute real-time profiles
Day-ahead	Hourly	Eight hours	Day ahead forecast	NREL day ahead forecast
Hours-ahead	Every 15 minutes	Two hours	Average of day-of forecast and actual 5-minute demand	NREL 4-hour ahead forecast
Real-time	Every 5 minutes	None	Actual 5-minute demand profile	Simulated 5-minute profile

Based on input from TECO, each class of thermal generator is assigned a final stage beyond which commitment decisions are not allowed to be changed (Table 2). This reflects operational practice where, as real-time approaches, commitments of relatively inflexible units cannot be changed. For combined cycle gas turbines, multiple configurations (e.g., 1x1, 2x1, etc.) are modeled with the steam turbine's commitment decision preceding the associated combustion turbine commitments.

Table 2. Timing of final commitment decisions for each generator class

Generator Class	Final Commitment Decision Made in Stage:
Coal integrated gasification combined cycle	Not economically dispatched (must-run)
Simple cycle coal steam turbine	Multiple days-ahead
Simple cycle gas steam turbine	Multiple days-ahead
Steam turbine of gas combined cycle	Day-ahead (or must-run, depending on unit)
Combustion turbine of gas combined cycle	Hours-ahead
Market transactions	Hours-ahead
Simple cycle gas combustion turbine	Real-time

Thermal generators are represented using standard unit commitment and dispatch constraints, including ramping limitations, minimum uptime and minimum downtime constraints, and co-optimized energy and reserve provision. Reserve calculations and requirements are described in Appendix A. Generator economics are reflected via heat rate curves, variable operations and maintenance costs, fuel offtake at startup, and startup costs. TECO also provided unit-specific maintenance and outage schedules. Consistent with current TECO dispatch practices, a price on CO_2 emissions was not included.

For simplicity of case construction and interpretation, market transactions with external entities are restricted to hours in which the TECO system does not have enough generation available to serve load. Market transactions are limited by hourly transmission availability data provided by TECO. Exports from the TECO system to external entities were not considered. In reality, TECO would have additional opportunities to deliver solar energy to external entities and reduce operating cost beyond what is simulated here.

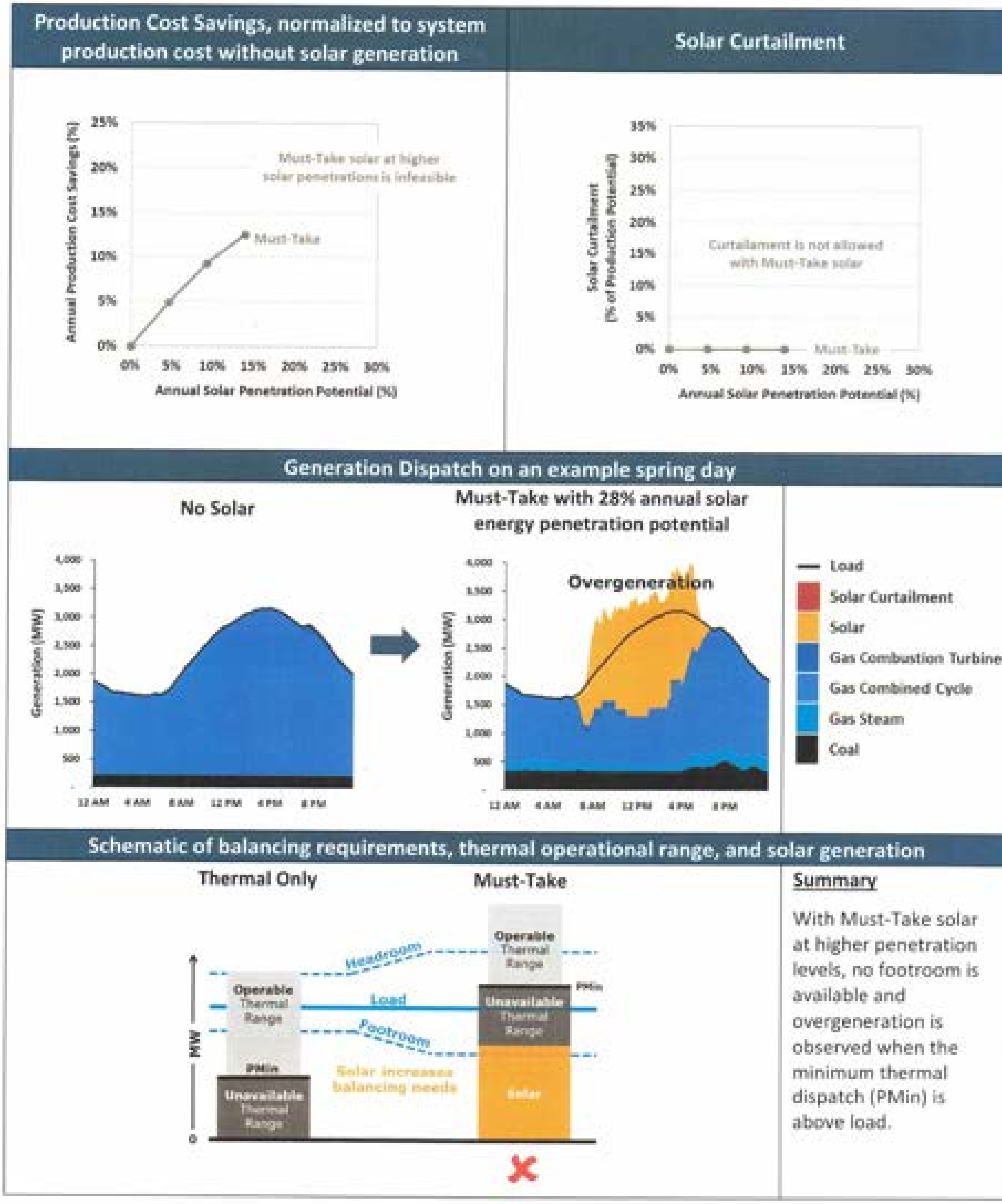
3 Flexible Solar Production Simulation Results

3.1 "Must-Take" operating mode: Limited by overgeneration

We first explore the limits of the Must-Take solar operating mode. We find that Must-Take solar can be absorbed by the TECO system up to about 14% of annual energy penetration potential. At solar penetrations above this level, we begin to observe overgeneration conditions, indicating that the system does not have enough flexibility to balance supply and demand while also accepting every MWh of solar generation. An example dispatch day demonstrating overgeneration conditions is shown in the middle panel of Figure 5. Solar penetrations above 14% on the TECO system are infeasible in Must-Take operating mode.

The appearance of overgeneration indicates that solar curtailment is a necessary tool to balance the system above a threshold level of solar penetration. This result is generalizable to any system, though the annual energy penetration threshold will depend on the characteristics of each individual system, including the load shape and the flexibility of its generation fleet. Shown schematically in the bottom panel of Figure 5, Must-Take solar at high solar generation levels can cause conflicting requirements to 1) accept all solar generation and 2) maintain headroom and footroom on thermal generation. Most thermal generators have minimum power (PMin) requirements; if turned on, a typical thermal generator must generate at a minimum of 20 – 50% of its rated capacity (PMax). The commitment decision for many generators must be made hours to days ahead of real-time, when the actual real-time solar output is not known with great certainty. Committing enough generation capacity to create the headroom and footroom required to plan for many possible levels of solar generation (cloudy to sunny) exhausts the operational range (PMin to PMax) of the thermal fleet. Our results demonstrate that planning to absorb all solar generation is untenable at higher solar penetration levels.

Figure 5: Summary: "Must-Take" Operating Mode



3.2 "Curtailable" operating mode: Feasible dispatch

A key indicator of inadequate operational flexibility is the curtailment of variable renewable generation. As shown in the top right panel of Figure 6, solar can contribute up to 14% of energy with very low levels of curtailment, indicating that the thermal generation fleet has adequate flexibility to integrate up to this level of solar generation with minimal challenges. Since very little solar curtailment is necessary at this level of solar penetration, increasing the flexibility of solar generation provides limited additional value.

At intermediate levels of solar penetration on the TECO system (~15 – 25% solar energy penetration), curtailing solar generation allows what would otherwise be an inoperable system with Must-Take solar to become operable. Curtailing solar enables more thermal generators to be committed, thereby creating enough space within the dispatch stack to maintain adequate headroom and footroom on thermal units (Figure 6, bottom panel). Even though the system is operable, curtailment levels resulting from this operational strategy become very high as more solar is added to the system. Adding more solar causes additional thermal units to be committed to meet increased operational reserve requirements. Committing these units causes more fuel to be burned in conventional generators, which in turn reduces the energy value of solar generation.

The energy value (Figure 6, top panel) on the TECO system of additional solar energy in Curtailable operating mode decays rapidly above about 14% solar energy penetration. The energy value (or, equivalently, the production cost savings) is calculated as the change in annual production costs as solar penetration increases, excluding the capital cost of additional solar resources. Solar provides very little marginal energy value at penetration levels above 19%. In the extreme – above 23% solar energy production potential – solar has a *negative* marginal energy value. This occurs because the increase in headroom and footroom required to balance solar forecast error is so large, and the fuel penalty for providing these reserves on thermal units so significant, that adding solar actually increases fuel consumption. The relatively small footprint of TECO's balancing area and solar resources contribute to the steep drop-off in energy value in Curtailable operating mode. The solar penetration level at which Curtailable operating mode becomes ineffective will be system-specific, but we expect that other systems will show similar dynamics as the level of solar generation is increased. Given the economic inefficiencies that result from Curtailable operating mode at higher levels of solar penetration, our results suggest that as more solar is deployed, system operators should adapt dispatch procedures to include more flexible solar plant operation.